IMPROVED FREQUENCY DOMAIN DECOMPOSITION AND STOCHASTIC SUBSPACE IDENTIFICATION ALGORITHMS FOR OPERATIONAL MODAL ANALYSIS

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DEDICATION

This thesis is dedicated to my beloved parents, who taught me that the best way to success is to work hard and be grateful for the result. They taught me that even the largest task can be accomplished if it is done one step at a time. To my family for their patience, support, love and prayers.

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ABSTRACT

The accuracy of the estimated modal damping ratios in operational modal analysis (OMA) remains an open issue and is often characterized by a large error. The modal damping ratio is considered to be a good practical parameter for structural damage detection due to its sensitivity and sufficient responsiveness to damage compared to natural frequency and mode shape. Therefore, an accurate estimate of the modal damping ratio will assist in developing an effective modal-based structural damage detection approach. The objective of this research focuses on improvements of frequency domain decomposition (FDD) and stochastic subspace identification (SSI) algorithms, particularly in estimating modal damping ratio. These methods have gained a lot of attention and interest compared to other OMA methods due to their ability in estimating modal parameters. However, FDD has a problem dealing with high damping levels, while SSI has difficulty in handling harmonic components. This will cause a large error in estimating the modal damping ratio. Difficulties also arise for automation of SSI as several predefined set parameters are compulsory at start-up for each analysis. This study introduces an iterative loop of advanced optimization to enhance the capabilities of classical FDD algorithm by optimizing the value of the modal assurance criterion (MAC) index and the selection of the correct time window on the auto-correlation function that represents the most challenging part of the algorithms. This study also presents the development of the SSI framework in automated OMA and harmonic removal method using image-based feature extraction along with the application of empirical mode decomposition. The implementation of image-based feature extraction can be used for clustering and classification of harmonic components from structural poles as well as to identify modal parameters by neglecting any calibration or user-defined parameter at start-up. The proposed approach is assessed through experimental and numerical simulation analysis. Based on the numerical simulation results, the proposed optimized FDD can estimate modal damping ratio with high accuracy and consistency by showing average percentage deviation (error) below 5.50% compared to classical FDD and benchmark approach, which is a refined FDD. Errors in classical FDD can reach an average of up to 15%, whereas for refined FDD the average is around 10%. Meanwhile, the results of the proposed approach in experimental verification show a reasonable average percentage deviation of about 5.75%, while the classical FDD algorithm is overestimated which averages about 29% in all cases. For the proposed automation of SSI, the estimated results of modal damping ratio in the numerical simulation are below 2.5% of the average error compared to other SSI methods which on average exceed 3.2%. For experimental verification, the results of the proposed approach indicate very satisfactory agreement by showing average deviation percentage below 4.20% compared to other SSI methods which on average exceeds 14%. Furthermore, the results of the proposed automated harmonic removal in SSI framework for estimating modal damping ratio using existing online experimental data sets demonstrate very high accuracy and consistent results after removing harmonic components, showing an average deviation percentage of below 7.22% compared to orthogonal projection and smoothing technique based on linear interpolation approaches where the average deviation percentage exceeds 9%.

ABSTRAK

Ketepatan anggaran nisbah redaman ragaman dalam analisis ragaman kendalian (OMA) masih tetap menjadi isu terbuka dan sering dicirikan oleh ralat besar. Nisbah redaman ragaman dianggap sebagai parameter yang sesuai untuk pengesanan kerosakan struktur kerana sensitif dan responsif terhadap kerosakan berbanding dengan frekuensi tabii dan bentuk ragam. Penganggaran nisbah redaman ragaman yang tepat dapat membantu pembangunan pendekatan pengesanan kerosakan struktur berasaskan ragaman yang berkesan. Objektif penyelidikan ini memfokuskan kepada pembaikan algoritma penguraian domain frekuensi (FDD) dan pengenalan subruang stokastik (SSI), terutama dalam anggaran nisbah redaman ragaman. Kaedah-kaedah ini telah mendapat perhatian berbanding dengan kaedah OMA yang lain kerana kemampuan menganggarkan parameter ragaman. Namun begitu, FDD mempunyai masalah dalam menangani tahap redaman yang tinggi, sementara SSI pula menghadapi kesukaran untuk mengendalikan komponen harmonik. Ini akan menyebabkan ralat yang besar untuk anggaran nisbah redaman ragaman. Kesukaran juga timbul untuk automasi SSI kerana beberapa parameter set wajib ditetapkan pada permulaan untuk setiap analisis. Kajian ini memperkenalkan gelung berlelar pengoptimuman lanjutan bagi meningkatkan keupayaan algoritma FDD asal dengan mengoptimumkan nilai indeks kriteria kepastian regaman (MAC) dan pemilihan tetingkap masa yang betul pada rangkap autosekaitan yang mewakili bahagian algoritma yang paling mencabar. Kajian ini juga mengutarakan pembangunan kerangka SSI dalam OMA automatik dan kaedah penyingkiran komponen harmonik dengan menggunakan penyarian ciri berasaskan gambar bersama dengan penerapan penguraian ragaman empirik. Pelaksanaan penyarian ciri berasaskan gambar dapat digunakan untuk gugusan dan pengelasan komponen harmonik dari kutub struktur serta digunakan untuk mengenal pasti parameter ragaman dengan mengabaikan sebarang penentukuran atau parameter yang ditentukan pengguna pada saat permulaan. Pendekatan yang dicadangkan dinilai menerusi ujikaji dan analisis penyelakuan berangka. Berdasarkan hasil penyelakuan berangka, FDD yang dioptimumkan dapat menganggarkan nisbah redaman ragaman dengan ketepatan dan konsistensi yang tinggi dengan menunjukkan sisihan peratusan (ralat) rata-rata di bawah 5.50% berbanding FDD asal dan kaedah tanda asas, iaitu FDD yang diperhalusi. Ralat dalam FDD asal boleh mencapai rata-rata sehingga 15%, sedangkan untuk FDD yang disempurnakan rata-rata adalah sekitar 10%. Sementara itu, hasil pendekatan yang dicadangkan dalam pengesahan ujikaji menunjukkan sisihan peratusan purata yang munasabah sekitar 5.75%, sementara untuk algoritma FDD asal terlalu tinggi yang rata-rata sekitar 29% dalam semua kes. Untuk automasi SSI yang dicadangkan, hasil anggaran nisbah redaman ragamam dalam penyelakuan berangka di bawah 2.5% dari ralat purata berbanding dengan kaedah SSI lain yang rata-rata melebihi 3.2%. Untuk pengesahan ujikaji pula, hasil pendekatan yang dicadangkan menunjukkan hasil yang sangat memuaskan dengan menunjukkan peratusan sisihan yang berada di bawah purata 4.20% berbanding kaedah SSI lain yang rata-rata melebihi 14%. Selanjutnya, hasil cadangan penyingkiran harmonik automatik dalam kerangka SSI untuk anggaran redaman ragamam menggunakan set data eksperimen yang sedia ada dalam talian menunjukkan ketepatan yang sangat tinggi dan hasil yang konsisten setelah menyingkirkan komponen harmonik, menunjukkan sisihan peratusan rata-rata di bawah 7.22% berbanding pendekatan yang lain, iaitu berdasarkan unjuran ortogonal dan teknik pelicin berdasarkan penentudalaman lelurus yang mana sisihan peratusan purata melebihi 9%.

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LIST OF ABBREVIATIONS

FDD	-	Frequency Domain Decomposition
SDOF	-	Single Degree of Freedom
MAC	-	Modal Assurance Criterion
SSI	-	Stochastic Subspace-Based Algorithms
OMA	-	Operational Modal Analysis
EMA	-	Experimental Modal Analysis
SVD	-	Singular Value Decomposition
PSD	-	Power Spectrum Density
LogDec	-	Logarithmic Decrement
HT	-	Hilbert Transform
NExt	-	Natural Excitation Techniques
CF	-	Correlation Function
SD	-	Spectral Density
SHM	-	Structural Health Monitoring
RUL	-	Remaining Useful Life
IMF	-	Intrinsic Mode Functions
EFDD	-	Enhanced Frequency Domain Decomposition
ODS	-	Operational deflection shape
TD	-	Time domain
FFT	-	Fast Fourier transform
ACF	-	Auto correlation function
EMD	-	Empirical mode decomposition

LIST OF SYMBOLS

δ	-	Logarithmic decrement
γ	-	Kurtosis value
ζ	-	Modal damping ratio
ω_d	-	Damped natural frequency in radian
ω	-	Undamped natural frequency in radian
ϕ	-	Mode shape vector
ε	-	Residual
λ	-	Eigenvalues
f_d	-	Damped natural frequency
f	-	Undamped natural frequency

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CHAPTER 1

INTRODUCTION

1.1 Problem background

The current issues involving the ageing and structural degradation of a numerous civil infrastructures as well as the construction of new complex structure with the high possibility of excessive vibration levels have brought about significant interest to engineering community on dynamic tests, vibration-based health monitoring and modal-based damage detection. Dynamic tests allow the identification of modal structural properties (natural frequencies, mode shapes and modal damping ratios) of relevant modes of vibration. These parameters are essential particularly for finite element model updating, tuning vibration control devices, safety inspection programs and for tracking the evolution of the corresponding structural dynamic characteristics.

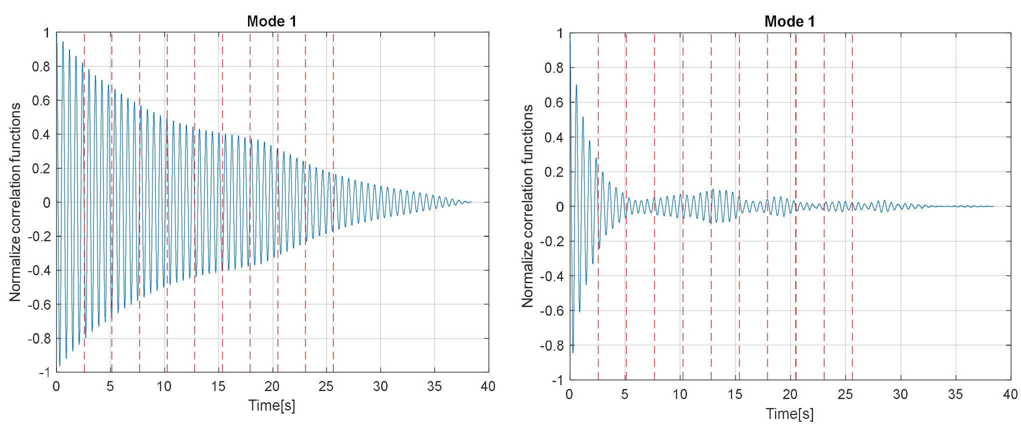
As civil engineering structures are often continuously excited by undetermined ambient excitations (operating loads, wind, turbulence, traffic), new techniques have been developed for the past decade in identification of modal parameters that rely solely on structural response signals induced by ambient excitations [1,2]. This type of dynamic test, defined as Operational Modal Analysis (OMA) is widely and commonly used in within various engineering field such as mechanical, aerospace, electrical and civil due to its capability to implement economical and fast tests without affecting its operating conditions [3]. This leads to the major advantages of OMA techniques compared to classical Experimental Modal Analysis (EMA) that requires input excitations for structural modal identification [1,2].

By taking the advantage of ambient excitation, which is always present, the techniques can be used for continuous structural health monitoring. This permits to track the evolution of modal parameters over time that can be used to detect structural integrity or problems due to structural deterioration, or the occurrence of damages on structure. For example, when the structure gets old, the value of modal parameter such as natural frequency will reduce over time due to loss of stiffness, while modal damping ratio will increase over time due to rusted steel. In general, the variation of natural frequencies over time is more apparent to be adopted as a parameter for damage detection due to consistent trend but, it has low sensitivity unless severe damage happened [4]. It is reported that less than 5% change in frequency associated with critical damage [5]. On the other hand, the use of modal damping ratio as a parameter to detect structural problems is more suitable as it is more sensitive to damage compared to natural frequency and mode shape. However, it is less popular among engineering community because of inconsistent trend [3][6]. Thus, an accurate identification of modal damping ratio will assist in developing effective and reliable modal-based damage detection approach for structures.

However, the accurate estimation of modal damping ratio using OMA is still an open problem because errors are greatly influenced by the magnitude of structural responses and the absence of input load in OMA. The difficulties encountered when trying to estimate modal damping from ambient vibrations has been discussed in [7]. The effective identification of modal damping relies on how good the fundamental mathematical model of the estimation method is. Other factors that potentially affect the estimation modal damping include test procedure and quality of measurements. Besides, significant dispersion of random and bias error in modal damping estimates for various mechanisms have been reported using available OMA techniques [8].

OMA methods can be categorized into time domain and frequency domain approaches. OMA methods that rely solely on the response time histories or correlation functions are denoted to as time domain methods, while the frequency domain techniques are based on the output power spectrum density (PSD). Frequency domain decomposition (FDD) that belongs to frequency domain techniques for OMA is capable of detecting modal frequencies and mode shapes of closely spaced modes or even repeated modes effectively. This method is less sensitive to ambient noise, since the adoption of singular value decomposition (SVD) is able to isolate the signal from noise. Structure with symmetrical form and even real structure often have closely spaced modes having closely located natural frequencies. However, FDD techniques seem to have the problem of providing a correct estimate of modal damping ratio, since the exact practical computation of modal damping is still an open issue and often leads to biased estimates. Nevertheless, natural frequencies and mode shapes can be computed confidently [3][9]. Moreover, the issue is getting worse when the current FDD method handles the response signals of the high-damped structure [10].

Typical characteristic assumptions for the validity of the FDD method are white noise input, very low structural damping ratios (below 1% of critical damping) and geometrically orthogonal mode shapes of closed modes. If these assumptions are not satisfied, the SVD decomposition may result approximated, leading to noisy plots and inaccurate results. Previous assumptions and procedures belong to classical FDD implementations, as stated from main literature works as [11–17]. Typically, the concrete civil structure is categorised as a low damped structure with modal damping ratio is lower than 1% of critical damping. On the contrary, for steel structures, the modal damping ratio is always larger than 1% of critical damping and considers as high damped structure [18]. The response will decay at a higher rate when the level of damping is higher, example as shown in Figure 1.1.



(a) (b)

Figure 1.1 Representation of the correlation function for (a) low damped and (b) high damped structure.

In contrast, time domain methods are quite sensitive to noisy conditions, influenced by close modes and difficult to accurately estimate number of vibrations mode [15]. Meanwhile, developments of OMA in time domain have increased substantially since the past decade. Despite the observed progress, some improvements still need to be done, especially in term of automated procedures, since traditional methods of modal analysis require the setting of several step or predefined set parameters and a large amount of intervention by an expert user [19]. Besides that, the elimination of environmental and operational effects such as harmonic components on modal parameters also need to be considered. A random response obtained from ambient excitations on civil engineering structures is often characterized by specific variability, commonly known as the “noise” due to environmental effects, which can lead to a big issue in obtaining a reliable result in modal parameter identification. There is also a significant issue regarding “noise” (or spurious) modes and automatically distinguishing them from physical modes still remains to be solved [20].

1.2 Problem statement

The response signals of high damped structure pose difficulty for the current FDD method, particularly for modal damping estimation, since FDD seems to be lacking on that because it contrary with the original specific assumption of FDD methods which can efficiently work only for low damped structures (modal damping ratios less than 1% of critical damping) [11,17,21]. When the response signals decay at a higher rate, the amount of correlated points in the correlation function will decrease and the fit becomes worse, as the nonphysical information from the noise becomes more dominant, thus the correlation will represent the signal noise rather than the physical system and and it tends to overestimate modal damping due to leakage in the estimated spectral density function [22][23]. The modal parameters identification of high damped structure becomes more difficult if the signals are polluted with noise [24]. However, FDD is capable of detecting modal frequencies and mode shapes in terms of closely spaced modes or even repeated modes, since SVD can isolate the signal from noise where other methods face difficulties in overcoming it [15].

Most of the researchers have tried to improve modal damping estimation by introducing a variety of techniques for modal damping estimation in FDD-type procedures such as logarithmic decrement (LogDec) method [14,25], Hilbert transform (HT) [15] and natural excitation techniques (NExt) i.e. cross-covariance function, Ibrahim time domain, and Polyreference [26] as well as the optimal wavelet [27]. Also, some researchers have tried tackling the signal processing issue by making improvements using their proposed method since the signal processing is denoted as the contributing factor for estimation errors comprising estimates of correlation function (CF) and the spectral density (SD) [23]. However, this issue is still considered as an open problem and unsolved because after throughout critical reviews and pilot tests, there is another factor that contributes to this error which is due to parameter extraction as shown in Figure 1.2, particularly in term of proper selection of the correct time window for extrema picking of single degree of freedom (SDOF) auto-correlation function and modal assurance criterion (MAC) index selection which turn out to be the most challenging part of the algorithm. Time window for extrema picking of SDOF auto-correlation function and MAC index selection need to be carefully chosen, otherwise it will lead to random and bias errors. Therefore, particular attention is needed for proper selection of the correct time window for extrema picking of a single degree of freedom (SDOF) auto-correlation function and MAC index selection. Currently, some researchers have tried to address this problem by introducing iterative loop optimization in selection of the correct time window, extrema picking of single degree of freedom (SDOF) auto-correlation function and MAC index selection. However, the results obtained from numerical simulation analysis are still not satisfactory enough and require for improvement. It is reported that the percentage deviation of estimated modal damping ratios was up to 15% and 10% on average. Meanwhile, the percentage deviation of estimated natural frequencies was less than 5% [10,12,28–32].

General step of frequency domain decomposition (FDD) method is illustrated in Figure 1.2.

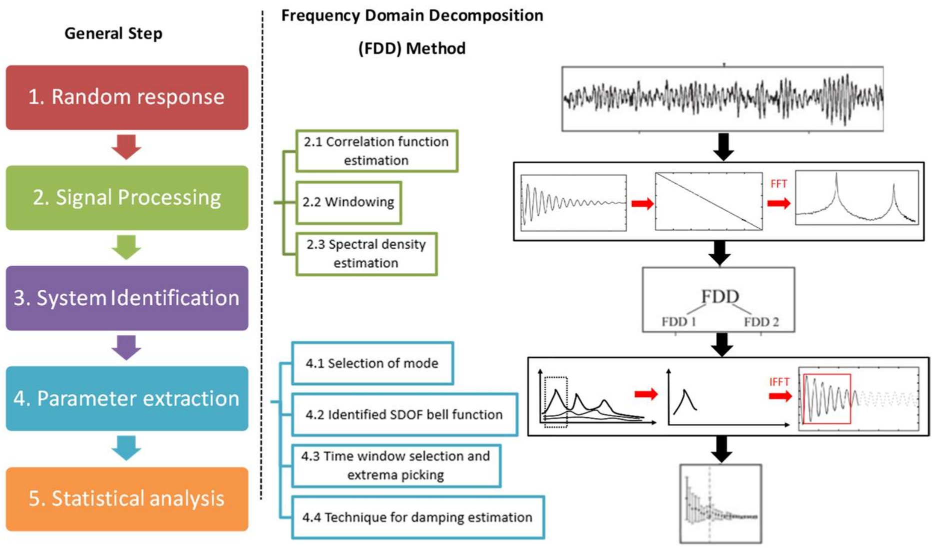


Figure 1.2 Schematic illustration of frequency domain decomposition (FDD) procedure.

In recent years, the development of automated procedures for identifying modal parameters in operating conditions has become increasingly popular and stochastic subspace-based identification algorithms (SSI) methods have been selected as the most practical tool for this procedure due to the consistency in modal parameters estimation especially under non-stationary noise excitations [33–43]. However, the use of subspace-based algorithms for OMA and SHM will be problematic when applied to structures with rotating machines, due to the harmonic excitations. Harmonic components are sometimes considered as virtual modes in the identification and potentially mistaken for being structural modes [44], thus might lead to potentially bias the estimation of the actual modes where the standard automated OMA approaches cannot be applied in a straight- forward way [45,46]. There are some common deficiencies have compromised the existing harmonic removal techniques regarding to discard the harmonic influence over the output signal without interaction with any expert user or additional knowledge of such, e.g. tachometer measurements still remain to be solved.

Difficulties arise for SSI method when automating this procedure without the need of any human interaction and the problem is still unresolved because, in the case of application of the advanced clustering algorithm, several predefined set parameters is compulsory at start-up for each analysis of the data set in order to estimate the maximum within-cluster distance between representations of the same physical mode from different system orders and the supplementary adaptive approaches have to be employed to optimize the selection of cluster validation criteria [9,36,39,47]. In addition, the values for thresholds for each modal parameter to separate physical from noise modes are inconsistent due to natural variations in modal properties of structures that come from damage or environmental influences that bring more difficulties to existing approaches [48].

Abovementioned literatures proved that calibration of parameters at start-up of structural vibration analysis should be avoided. These harmonic components will cause uncertainty in extraction of modal parameters by disturbing the identification of actual structural modes as it appears in the form of natural frequency and mode shape [49] and it need to be detected and removed before modal identification. Recently, this has been recognized and most of the researchers agree more attention should be paid to that [47]. Thus, an alternative approach was required to automate this procedure without the need of any human interaction or additional knowledge regarding to a known rpm-time profile. It is possible to remove unwanted signal (harmonic components) from its raw signal, but more attention should be paid to ensure all the necessary information from this signal are not affected because it should be noticed that harmonic components cannot, in general, be removed by simple filtering as this would in most practical cases significantly change the poles of the structural modes and thereby their natural frequency and modal damping.

1.3 Research objectives

The main purpose of the present research is to improve the accuracy and provide unbiased results of the estimated modal parameter, particularly for modal damping ratio by introducing a new approach for frequency domain decomposition (FDD)- based method for both type of structure (low and high damped structure) and a desirable solution for harmonic removal within the stochastic subspace-based identification algorithms (SSI) framework. Furthermore, these introduced algorithms can work for both numerical and experimental data. To achieve this target, several objectives have been highlighted for this research which includes:

(a) To develop improved algorithm that can enhance the classical FDD algorithms by optimizing the correct time window selection for extrema picking of a single degree of freedom (SDOF) auto-correlation function and MAC index selection

(b) To develop clustering algorithm for automation of SSI that can avoid any calibration of parameters at start-up of structural vibration analysis and can ensure an effective identification of physical modes.

(c) To develop automated harmonic removal technique in the SSI method for effectively identifying and discarding the influence of harmonic components over the output signal and then automatically reconstructing it without leaving any necessary information regarding to structural mode.

1.4 Scope of work

The scope of this research:

(a) The considered structural system is linear and time-invariant as commonly applied in OMA method [9,50,51].

(b) Low and high damped structures are used to evaluate the proposed optimized FDD. In numerical simulation, modal damping ratio of low damped structure is set to be lower than 1% of the critical damping, while modal damping ratio of high damped structure is set to be more than 1% which is from the range of 2% to 5% of the critical damping [10,18]. For experimental verification, fluid damper is used at the base of steel frame mimic the high damped structure while the low damped structure make do without.

(c) Structure that having a rotating machine which produces the harmonic excitations is used to validate the proposed automated harmonic removal technique. In the numerical simulation, this condition is represented by a structure subjected to random excitation combined with additional steady-state signal.

(d) Numerical simulations (simulated signal analysis) are performed in MATLAB on simple multi storey shear-type models which consists of two, three and six degrees of freedom (DOF). The multi storey shear-type models present well-separated modes. The damping employed in the structure is viscous (damping forces proportional to velocity) and proportional Rayleigh damping.

(e) Experimental verification is performed using 900cm x 420cm three storey steel frame for proposed optimized FDD and the structural sample of a square aluminium plate with dimensions of 100cm x 100cm x 0.4cm for automated harmonic removal technique. In addition, the experimental tests on plate using online database is also used to validate the proposed automated harmonic removal technique with existing harmonic removal approaches that conducted by Niels-Jørgen Jacobsen from B&K Nærum, Denmark.

(f) The random input excitation response of the system in the numerical simulation was simulated using Newmark's method with constant average acceleration, while for experimental verification, a shaking slip table and hand taping with fingertips are used to induce the random input excitation for the three-storey steel frame and aluminium plate respectively.

(g) The acceleration signals are measured with accelerometers (Wicoson) and amplified with ICP sensor signal conditioner. The signals were sampled by OROS data acquisition equipment which is connected to a computer. The selected accelerometer frequency range is suitable to the measured structure which is 0 to 250 Hz.

1.5 Significance of the study

Careful treatments of spectral bell width, singular value, time window selection and extrema picking had become important issues in achieving reliable estimate of natural frequencies and mode shapes in FDD by using the proposed advanced optimization method. This research aimed to provide a reliable and consistent result at variable proportional damping level. Besides that, this aims to provide an effective solution to identify and discard the harmonic influence from the output signal by neglecting any calibration or user-defined parameter at start-up and then automatically reconstruct back the output signal. The proposed algorithm will optimize the time window selection for extrema picking and MAC index selection of FDD algorithm for modal dynamic identification of structures. The developed automated harmonic removal method in the SSI framework is expected to serve as basis for future studies in enhancing the automation of OMA method. The accurate and precise values of modal parameters can provide a better and reliable data for health assessment as well as more comprehensive and accurate fault coverage. These techniques will improve the prognostic or prediction of remaining useful life (RUL) of the structure which can extend the structure's design life.

1.6 Thesis outline

This thesis consists of five chapters. The second chapter in this thesis presents a literature review on the state-of-the-art approaches of OMA as the structural health monitoring technique. The review discusses on the OMA methods, development of the automated procedure, advantages and limitation as well as the current solutions to the limitations. This chapter highlights the research gaps. Chapter 3 covers the steps of the theoretical formulation of the proposed approaches for optimized FDD and automated harmonic removal technique. Chapter 4 presents and discusses the preliminary analysis using the proposed approaches on the simulated white noise input on a multi-storey frame. The performance of optimized FDD is evaluated for the low and high damped structures, while the validation of automated harmonic removal technique is done with the addition of harmonic excitation. The results of the proposed approach in numerical simulations are validated using eigenvalue problem analysis and compared with classical approach. Chapter 5 presents the details of the experimental setup. The results of the experimental study on the three-storey steel frame and aluminium plate are presented with cross validation techniques. Chapter 6 covers the comparative analysis of proposed automated harmonic removal with existing approach using online database. Chapter 7 summarises the findings, as well as the contributions of this study. The recommendations for future research are presented in this chapter.

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2. M. Danial A. Hasan [1,2*], Z. A. B. Ahmad[1,2], M. Salman Leong[1] and L. M. Hee[1], "Enhanced frequency domain decomposition algorithm: A review of a recent development for unbiased damping ratio estimates", Journal of Vibroengineering, JVE International (Q4)

3. M. Danial A. Hasan [1,2*], Z. A. B. Ahmad[1,2], M. Salman Leong[1] and L. M. Hee[1], "Automated denoising technique for random input signals using empirical mode decomposition (EMD)- stabilization diagram", MATEC Web Of Conferences, Engineering Applications of Artificial Intelligence Conference (EAAIC 2018), Kota Kinabalu, Sabah, Malaysia, 3rd to 5th December 2018 (SCOPUS)

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